Zeitschrift: Helvetica Physica Acta
Band: 27 (1954)
Heft: VI

Artikel: Coherent meson processes
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DOI: https://doi.org/10.5169/seals-112528

Coherent Meson Processes

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(24. IX. 1954.)

Elastic production of π^0 by photons on D[1]) and He[2]) was recently observed. The former seems to indicate a coherent addition of the π^0 amplitudes stemming from the neutron and the proton. This was interpreted as evidence for a symmetrical theory since in lowest order the π^0 amplitude is proportional to the coupling constant and the magnetic moment, both having opposite signs for proton and neutron. Generally the amplitudes produced by a proton or a neutron have the same or the opposite sign, depending on whether the photon acts in isotopic spin space as the third component of a vector or as a scalar respectively[3]). As D has isotopic spin zero only the vector part is effective in elastic mesonproduction. The experimental evidence proves nothing but the presence of an appreciable vector part. This is consistent with the assumption that the π^0 production goes through an 3/2, 3/2 + state, in which case the photon supplies, of course, one unit of isotopic spin. It is not true, however, that in this case the elastic cross section is simply (atomic number)$^2\cdot$(formfactor)$^2\cdot$(nucleon cross section). One has to remember that the amplitudes add coherently only for the process without spin-flip.

The matrix element for π^0 production by a magnetic dipol transition of a nucleon through a 3/2, 3/2 + intermediate state can be written[4]):

$$T = (q_m^+ | 2\,\delta_{mn} + i\,\varepsilon_{jmn}\,\sigma_j\,|\,e_n)\,\frac{1}{3}\,t\,e^{i\,x(q-k)} \tag{1}$$

q and k are the momentum vectors of the meson and the photon respectively and e is a unit vector in direction of the magnetic field. Because there are only p-mesons in the final state we shall express the properly normalized state vector $(q|$ by its cartesian components, e.g. $|q) = (1, \mathrm{i}, 0)\,2^{-\frac{1}{2}}$ means $|q) \sim q_x + i q_x$. t is a function of q and k. In the applications to complex nuclei we assume, as usual, that t does not depend on the nucleon momentum. This assumption is born out by a field theoretical calculation as long as the nucleons are not relativistic. Taking for e_n the vector $(1, i, 0)2^{-\frac{1}{2}}$ we obtain on squaring and averaging[1]) over the nucleon spin directions the following cross section for π^0-production on a free nucleon:

$$d\sigma_{\text{free}}/d\Omega = \frac{t^2}{2}\left(\sin^2\vartheta + \frac{\sin^2\vartheta}{9} + \frac{2}{9}\,2\cos^2\vartheta\right). \tag{2}$$

The first term corresponds to the nucleon spin parallel to the photon angular momentum. There is no spin-flip in this case and the meson takes over the angular momentum of the photon. $|q) = (1, i, 0)2^{-\frac{1}{2}}$, $d\sigma \sim \sin^2\vartheta$). For the nucleon spin in the opposite direction there is in addition to the $\sin^2\vartheta/9$ term, a spin flip term $((q| = (0,0,1)$, $d\sigma \sim 2\cos^2\vartheta$). (2) has been normalized arbitrarily.

For elastic π^0 production on a deuteron we get a coherent (non flip) contribution if $|q) = (1, i, 0)2^{-\frac{1}{2}}$. Let T_1^c (T_2^c) denote the coherent part of the transition matrix for the first (second) nucleon and ψ_D the wave function of the deuteron. On squaring and averaging $(\psi_D^+|T_1^c + T_2^c|\psi_D)$ over all three directions of the deuteron one obtains

$$d\sigma^c/d\Omega = \frac{4\,t^2}{3\cdot 9}\left((2+1)^2 + 2^2 + 1\right)\sin^2\vartheta\,|f^2| = 4\,\frac{14}{27}\,t^2\,|f^2|\sin^2\vartheta \tag{3}$$

$f(\vartheta)$ denots the form factor $\int dx\,|\psi_D(x)|^2\,e^{ix(k-q)}$.

Since the deuteron has a non vanishing angular momentum there is also an elastic spin flip process $(|q) = (0,0,1)$ where the deuteron as a whole changes its spin direction*). In this process, however, the amplitude, is not twice the nucleon amplitude, since

$$\left(\uparrow\uparrow|\sigma_1^+ + \sigma_2^+|\frac{\uparrow\downarrow+\downarrow\uparrow}{\sqrt{2}}\right) = \sqrt{2}, \text{ whereas } (\uparrow\uparrow|\sigma_1^3 + \sigma_2^3|\uparrow\uparrow) = 2\,.$$

The cross section for this process is worked out to

$$d\sigma^f/d\Omega = \frac{16\,t^2}{27}\,|f^2|\cos^2\vartheta \tag{4}$$

which gives a total

$$d\sigma_D/d\Omega = 4\,\frac{t^2}{27}\,|f^2|\,(4 + 10\sin^2\vartheta)\,. \tag{5}$$

For 90^0 the simple coherence argument is about correct, $d\sigma_D(90^0) = 4|f^2|\frac{14}{15}\,d\sigma_{\text{free}}(90^0)$, but it overestimates the cross section at 0^0 because of the suppression of the flip term:

$$d\sigma_D(0^0) = 4\,|f^2|\,\frac{2}{3}\,d\sigma_{\text{free}}(0^0)\,. \tag{6}$$

*) We regard the spin in the deuteron as a good quantum number, e. g. neglect the ^{3}D admixture.

This effect is even more pronounced for nuclei with zero angular momentum where the flip term is absent. In this case one gets

$$d\sigma_A/d\Omega = A^2\,|f^2|\,t^2\,\frac{4}{9}\sin^2\vartheta\,. \tag{7}$$

We illustrate the effect of the absence of T' by plotting $R(\vartheta) = d\sigma_A/A^2\,|f^2|\,d\sigma_{\text{free}}$ in Fig. 1. This might explain why there is, according to data available at present, no pronounced coherence effect

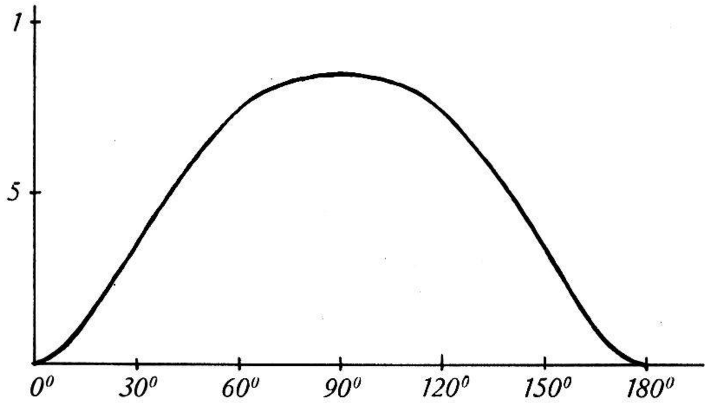

Fig. 1.

on carbon[5]): for large angles f is small and at small angles the coherent cross section decreases rapidely. GOLDWASSER et al. observed at 150^0 near threshold that the elastic cross section on helium is 4 times the free cross section. This means that the coherence effect is suppressed by a factor 4 which seems plausible because

$$d\sigma_A(150^0) = A^2\,|f^2|\,\frac{4}{11}\,d\sigma_{\text{free}}(150^0)$$

and f^2 is in this case about $0\cdot 7$. The form factor is for small momentum transfer insensitive to the shape of the nucleus and depends only on $\langle r^2\rangle$. This quantity has been determined quite accurately for some nuclei.

We remark finally that caution has to be observed when anomalous scattering of γ-rays on complex nuclei is compared with the scattering by a free proton. Apart from quenching of mesonic effects in complex nuclei there will be a reduction as spin flip amplitudes do not add coherently. An anomalous scattering due to a transition in a 3/2, 3/2+ state gives a scattering matrix[6])

$$T = a(e_1'\cdot e_2') + b\left[(e_1\cdot e_2)\,2 + i\,(e_1\times e_2\cdot\sigma)\right]\frac{1}{3} \tag{8}$$

e' is the direction of the electric field. We obtain for a proton

$$d\sigma_{\text{free}}/d\Omega = |a^2|(1+\cos^2\vartheta) + |b^2|\,(7+3\cos^2\vartheta)/9 + \frac{3}{8}\cos\vartheta.\,\mathrm{Im}\,ab^+ \tag{9}$$

and for a nucleus with $J = 0$

$$d\sigma_A/d\Omega = A^2 |f^2| [(1+\cos^2\vartheta)\,(|a^2| + 4\,|b^2|/9) + \frac{8}{3}\cos\vartheta.\ \mathrm{Im}\ ab^+]. \quad (10)$$

For $a = 0$ we get for instance

$$d\sigma_A(135^0) = \frac{12}{17} A^2\,|f^2|\, d\sigma_{\mathrm{free}}(135^0)\,.$$

This work was supported by the Schweizerischer Nationalfond.

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